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Highlights

- Background atmospheric conditions contributes to explain daytime intra-urban temperature variability
- Temperature variations tend to be more accentuated in less stable atmospheric classes
- Variability in air temperature is mostly noticed in urban canyons and less so in open- air situations

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Abstract

This study investigates the joint effect of atmospheric conditions and urban morphology, expressed as the Sky View Factor (SVF), on intra-urban variability. The study has been carried out in Glasgow, UK, a shrinking city with a maritime temperate climate type, and findings could guide future climate adaptation plans in terms of morphology and services provided by the municipality to overcome thermal discomfort in outdoor settings. In this case, SVF has been used as an indicator of urban morphology. The modified Pasquill-Gifford-Turner (PGT) classification system was adopted for classifying the temperature monitoring periods according to atmospheric stability conditions. Thirty two locations were selected on the basis of SVF with a wide variety of urban shapes (narrow streets, neighbourhood green spaces, urban parks, street canyons and public squares) and compared to a reference weather station during a total of twenty three transects during late spring and summer in 2013. Maximum daytime intra-urban temperature differences were found to be strongly correlated with atmospheric stability classes. Furthermore, differences in air temperature are noticeable in urban canyons, with a direct correlation to the site's SVF (or sky openness) and with an inverse trend under open-air conditions.

Keywords

Intra-urban temperature differences; atmospheric stability; urban morphology; climate change; urban design

INTRODUCTION

Although the disadvantages of nocturnal overheating due to urbanization in warm climate locations are well recognised, Urban Heat Island (UHI) effects in cold climate cities can still be a matter of dispute. For example, London's UHI phenomenon had many advantageous connotations in the 1960s (e.g., longer growing season, lower heating requirements, less de- icing on railway tracks [1]). Yet, after less than 40 years, overheating caused by UHIs was recognised as a problem [2,3,4] and policies for mitigation and adaptation have been established [5,6].

In the context of climate change, the importance of tackling inadvertent UHI effects has been increasingly recognised. This is due to both current urbanization trends and to the growing intensity of risks facing cities, often affecting environmental conditions and the quality of urban life. Appropriate urban planning options could help ameliorate the UHI problem and urban microclimate, thereby reducing climate change-related risks [7]. In addition to mitigating climate change by reducing greenhouse gas emissions, heat management is needed in cold climate cities in terms of using it as a resource in winter whereas ameliorating negative consequences in summer [8]. However, the role of cities in climate change adaptation is only beginning to be addressed [9], with vague and uncertain city-specific urbanclimate change action plans. In particular, studies that relate urban form to climate change are still scarce [10].

To reduce the risk of overheating due to climate change and as a means of mitigating negative consequences of UHIs, the effectiveness of certain urban forms needs to be explored when accounting for seasonal changes and background atmospheric conditions. Given the increasing interest in climate change adaptation and the use of models to evaluate the efficacy of various adaptations [11], such an assessment would further enhance their extent.

Background

The UHI effect in cold climate cities is well known. For example, comfort, energy and health implications of UHIs in cold climate cities (e.g., London) are well described by Mavrogianni et al. [12]. More interest in this subject is likely to arise in the coming years due to growing changes in global climate. In this sense, Kershaw et al. [13] developed methods to predict the UHI effect infuture climate projections for the UK.

Exploring land use and meteorological aspects of UHIs in Szeged, Hungary, Unger et al. [14] reported strong relationships between urban thermal excess and distance from the city centre, and between urban thermal excess and the built-up ratio. However, the authors were not able to relate significant correlations between meteorological conditions and UHI intensity.

In recent years, there has been more recognition of the need for more careful analysis of background atmospheric conditions [15,16] and synoptic weather patterns [17,18] when carrying out UHI measurements. As observed in a study on the shortcomings of UHI monitoring and simulation techniques [19], UHIs develop from small-scale processes such as human metabolism and meso-scale interactions such as atmospheric forces. Kolokotsa et al. [17] indicated that anticyclonic conditions greatly contribute to the development of UHIs during summer; they used a classification of synoptic conditions developed by Kassomenos [20] as a reference to investigate the UHI effect in Chania, Greece.

Krüger and Emmanuel [21] estimated the effects of background atmospheric conditions on UHIs and intra-urban air temperature in Glasgow, UK. They found that the range of intra- urban air temperature variability and warming trends at specific urban locations relative to a rural condition were accentuated when atmospheric stability is taken into account during field observations. For understanding urban morphology effects on such relationship with a set of air temperature stations, authors used the Sky View Factor (SVF) as indicative of morphology attributes at each location surveyed. The relationship between the site's SVF and local warming was found to be more pronounced under given atmospheric conditions.

The effect of urban geometry, as expressed by the site's SVF, on microclimate is one of the most studied aspects of UHIs. An early attempt to statistically relate urban geometry and microclimate was first reported by Oke [22].Unger [23] shows a detailed review of subsequent efforts.

A review of the relationship between SVF and urban air temperatures found it to be rather weak and contradictory [24]. Strong relationships have been reported in specific parts of a city (such as downtown areas), in Göteborg, Sweden ($R^2 = 0.78$) [25]. Long-term measurements encompassing larger areas showed, however, weaker relationships, as in a study analysing the entire urban area of Szeged, Hungary ($R^2 = 0.47$) [23]. A number of studies on the relationship between the SVF and daytime thermal effects show divergences, some suggesting a relationship between urban geometry, defined by the SVF, and ambient temperature [23,25,26], others demonstrating negligible impacts of the SVF on local temperature [27,28].

Eliasson and Svensson [29] showed intra-urban temperature variations reaching up to 9°C based on data collected during an 18-month period at 30 sites in Göteborg, Sweden. Their work focused not only on nighttime variability but also on daytime differences (solar noon, or 12 pm, local time), thereby allowing comparisons between day and night conditions. Weather conditions at the times of the field observations followed a cloudiness/wind classification (clear, cloudy sky, windy, calm). Monitoring sites ranged between dense urban locations to green spaces, with SVF ranging 0.7-1.0. Results showed that, in general, temperature variations are more dependent on weather than season, the highest correlations (between air temperature and surface cover) were found for clear, calm conditions, irrespective of season. However, for daytime conditions, variability was more frequent during cloudy conditions, irrespective of wind speed. Authors concluded that statistically significant temperature differences do exist between densely built-up areas, large open areas and green areas during windy and cloudy situations, both during day and night. For clear sky conditions, the lack of statistical significance can be attributed to the small amount of clear days during the monitoring period.

Konarska et al. [30] report findings from a field study involving long-term (two consecutive years) air temperature measurements in Göteborg, Sweden. Intra-urban thermal variations were analyzed at ten fixed park and street sites characterized by different types and density of vegetation, building geometry, openness and surface cover. The study showed the importance of such spatial characteristics in analyzing intra-urban variability in daytime and nighttime air temperature. Although most of the sites had some vegetation, with consequent foliage shading and evapotranspiration interfering effects (Park Cool Island 'PCI' effect), the relationship between openness and local air temperature during daytime in the warm half of the year (May-September) was positive i.e. followed a direct relationship.

Scott et al. [31] deployed a network of low-cost sensors ('iButtons') to analyze the intra- urban temperature variability in Baltimore, United States. The amount of weather stations employed was quite significant (135+ sensors) in that study, though the variability in terms of landscape was low, most sites with significant presence of vegetation. Results showed small intra-urban temperature variability (as regards daily minima). Authors concluded, from linear regression analysis that the presence/absence of vegetation is the only reliable predictor of mean air temperature among the various aspects examined such as albedo, tree-canopy cover, and distance to the nearest park.

The aim of the present study is to understand the effect of background atmospheric patterns on intra-urban temperature variability under warm conditions in the maritime temperate climate city of Glasgow, UK. Previousl y publishe d material on Glas gow's UH I [32] point to a warming trend during the last decades. Considering that local UHI still persists despite the fact that Glasgow can be classified as a shrinking city (with a significant decrease in population over time), the rationale behind the present study is to investigate the intra-urban temperature variability and its main drivers as regards urban morphology. From previous findings of an outdoor thermal comfort study carried out in downtown Glasgow, internationally established comfort limits were found not to conform to thermal preference of local population [33], suggesting a lower onset of thermal discomfort due to heat expressed in terms of the human thermal comfort index PET ('Physiological Equivalent Temperature' [34]). Both facts, i.e. the need for the city to adapt to climate change and the diminished tolerance of Glaswegians to warm climatic conditions, point to the relevance of the study.

From the understanding of the true impact of morphology on intra-urban temperature variability under clearly identified weather patterns, future analyses can more appropriately address urban design strategies for improving microclimate and, thus, contribute to a rise of urban quality of life in the study location.

METHOD

The need for tackling possible health impacts of heat-wave episodes, which will likely increase in frequency due to global climate change, as pointed out by Koppe et al. [35], requires effective interventions, measures and policies to protect the health of vulnerable Europeans in summer. We investigate the relationship between urban morphology on local air temperature profiles accounting for background atmospheric conditions during the short periods of field monitoring. The research further contributes to findings obtained in a previous study, where Krüger and Emmanuel [21] evaluated the effect of atmospheric stability on ambient temperature differences using a pair of stationary (urban vs. rural) weather stations and intra-urban differences with a set of temperature/relative humidity stations for the same city location.

The present study was carried out in Glasgow, UK (55°52'N, 4°15'W), a high-latitude location with climate type "5C" [36], cool, marine[1] and with approximately 600,000 inhabitants. According to the Koeppen-Geiger climate classification system, Glasgow lies within a region with temperate climate with maritime influences (Cfb). The mean maximum temperatures in the warmest season (July and August) is lower than 20ºC while mean daily temperature is over 10ºC at least during five months of the year [37].

As a continuation of past research initiatives, the study is served by two relevant databases: mobile air-temperature traverses carried out during summer in 2013 and outdoor thermal comfort campaigns conducted in 2011. The 2013 data were needed for assessing possible relationships between morphology and local air temperature whereas the 2011 database allowed us to put obtained results into the perspective of thermal comfort, as perceived by local population as well as to classify most recent summer conditions in terms of stability classes. Results are structured as follows: 1) classification of atmospheric stability of the days

with mobile traverses; 2) comparison betwe en mor pholog y attributes (ex pressed as the site's SVF) and air-temperature differences to the reference weather station; 3) correlation analyses of data subsets; 4) assessment of thermal comfort/discomfort levels during the traverses; 5) representativeness of the PGT atmospheric classes when compared to a longer series of summer data.

Mobile traverses were performed for measuring air temperature in selected points in the central area with differing urban morphology attributes. A reference weather station (Davis Vantage Pro2) was used, sited on the rooftop of a low-rise building (at approximately 10m above ground) on the central city campus of the Glasgow Caledonian University (GCU).

Air temperatures were measured on 23 days during spring and summer 2013 for a total of 32 visiting points. The urban area wherein traverses took place was selected according to a previous study by Emmanuel and Loconsole [38] where authors used the LCZ classification [39] for Glasgow from LIDAR data available with local authorities in order to identify potential problem areas as regards overheating in summer. The city centre area (Glasgow City Centre West and Glasgow City Centre East) was categorized as the LCZ class 'compact midrise'.

Three main routes (eastbound, central and westbound, as shown in Figure 1) were defined to access all 32 points as expedite as possible within the boundaries of the area of analysis. At each point, a

[1] From weather files available at https://energyplus.net/weather. Weather data for Glasgow are assumed as at the nearest weather station in Oban, 56°25'N, 5°28'W, 4m a.s.l. (Note that the ASHRAE classification shown here is derived algorithmically from the source weather data. It may not be indicative of the long-term climate for each location).

two-minute monitoring time was allowed, assumed to be sufficient to capture slight changes in air temperature readings during the area covered on foot and/or on a bicycle. Air temperature data were sampled every 10 seconds and averaged after discarding the first minute in order to account for the sensor's stabilization time. Mobile traverses started at 2:30 pm local time (near the peak air temperature, typically around 3:00 pm) and lasted approximately one hour. Eastbound and westbound routes were covered on bicycle while central route was done on foot.

Figure 1: Study area with monitoring points and traverses

The reference weather station, a Davis Vantage Pro2 weather station was set up at Glasgow Caledonian University and equipped with temperature and humidity sensors, a cup anemometer with a wind vane and pyranometer. For the traverses, we used small data loggers (Tinytag TGP-4500) enclosed in naturally ventilated radiation shields (ACS-5050, Stevenson Type Screen).

Urban morphology was determined by the site's Sky-View Factor (SVF), as measured by fisheye-lens photographs (SIGMA 4.5mm f 2.8 EX) and computed using RayMan Pro [40]. In terms of SVF, the sampling points represented a wide variety of urban forms (narrow street canyons, green areas, urban parks, uniform and non-uniform street canyons and public squares) (Table 1).

Table 1: Traverse points' specifications (SVF) and fisheye images

Point	SVF	Fisheye image	Point	SVF	Fisheye image	Point	SVF	Fisheye image	Point	SVF	Fisheye image
1	0,6		9	0,2		17	0,3		25	0,5	
2	0,4		10	~0,0		18	0,3		26	0,6	
3	0,2		11	0,3		19	0,2		27	0,4	
4	0,4		12	0,3		20	0,6		28	0,4	
5	0,3		13	0,4		21	0,3		29	0,5	
6	0,4		14	0,3		22	0,3		30	0,6	
7	0,1		15	0,3		23	0,3		31	0,7	
8	0,2		16	0,2		24	0,3		32	0,8	

Atmospheric stability was classified using the modified Pasquill-Gifford-Turner (PGT) classification ([41], modified by Mohan & Siddiqui [42]; Table 2) from data retrieved from the Weather Underground station 'Glasgow EGPF' (https://www.wunderground.com/weather/gb/glasgow), comprising wind speed and solar radiation data. For that, daytime classes were defined according to the mean wind speed and maximum solar radiation observed during the monitoring period.

Table 2: PGT atmospheric stability classes

WS (m/s)	Daytime SR (W/m²)				Night time CC (octas)		
	High[1]	Mod[2]	Low[3]	Cloudy	Low[4]	Mod[5]	High[6]
≤2	A	A-B	B	C	G-F	F	D
2-3	A-B	B	C	C	F	E	D
3-5	B	B-C	C	C	E	D	D
5-6	C	C-D	D	D	D	D	D
>6	C	D	D	D	D	D	D

Legend: WS wind speed, SR global solar radiation, CC cloud cover, [1] (>600), [2] (300-600), [3] (<300), [4] (0-3), [5] (4-7), [6] (8), A (highly unstable or convective), B (moderately unstable), C (slightly unstable), D (neutral), E (moderately stable), and F (extremely stable), G (extremely stable, low wind).

Finally, in order to translate local air temperatures to felt temperatures in terms of comfort/discomfort, the database obtained from outdoor comfort campaigns in Glasgow [34] was used for relating thermal sensation of passersby to ambient temperatures. Monitoring campaigns took place during late winter, spring and summer 2011, in pedestrian downtown streets within the circumscribed area (Figure 1), at six monitoring points. In those campaigns, meteorological variables were monitored according to ISO standard 7726 [43] with a Davis Vantage Pro2 weather station, equipped with temperature and humidity sensors, cup anemometer with wind vane, silicon pyranometer and gray-painted globe thermometer. The weather station was positioned next to the passerby and variables were measured close to the person (approximately 1.5 m) except for the anemometer and pyranometer, which were placed just above head height (at about 2 m) so that both interviewer and respondent would not affect wind speed readings. Surveys were conducted during daytime, usually between 10 am and 1 pm. Excluding outliers and respondents who did not meet the criteria of long-term and short-term acclimatization, the sample size for Glasgow was 567 respondents over 19 monitoring campaigns.We used a thermal comfort questionnaire consisting of items related to gender, age, height, weight and clothing; residency time in Glasgow (exclusion criterion: less than six months) and exposure time to the outdoors prior to the interview (exclusion criterion:at least 15 minutes); thermal perception and thermal preference. Concerning the perceptual evaluation (thermal sensation vote, or TSV), the basic question was “How do you feel at this exact moment?”, using the symmetrical 7-degree two-pole scale ranging from -3 (“cold”) to +3 (“hot”), whose responses are, in this paper, solely correlated to ambient temperature concurrently monitored next to the interviewed person. A thorough description of the survey conditions is shown in [33].

RESULTS

The arrangement of the daytime periods according to their PGT classes is given in Table 3, along with temperature, measured at the weather station at GCU, wind speed and solar radiation attributes during the transects, as measured at the Weather Underground station ‘Glasgow EGPF’.

Table 3: Array of transect days, climate descriptors and corresponding PGT classes

Date	Minimum Temperature (°C)	Maximum Temperature (°C)	Wind Speed (m/s)	Solar Radiation (W/m²)	Atmospheric Stability Class (PGT)
May 21	18.2	19.3	1.8	591	A
July 18	28.0	28.6	1.2	816	A
July 19	27.5	28.5	1.1	779	A
May 22	14.5	15.9	2.4	656	A-B
May 30	19.3	19.9	1.9	359	A-B

June 5	19.7	20.8	1.1	330	A-B
June 6	21.5	23.3	0.4	549	A-B
June 7	19.7	20.3	2.5	816	A-B
June 17	19.6	20.6	0.5	398	A-B
June 18	20.8	22.3	1.8	539	A-B
June 26	19.3	20.4	2.6	830	A-B
August 13	19.0	23.8	2.1	699	A-B
May 20	22.9	23.8	2.1	514	B
May 29	18.7	19.5	1.0	207	B
June 19	19.2	20.0	2.9	589	B
June 25	17.9	18.6	2.6	363	B
June 27	12.8	13.1	1.5	130	B
July 1	15.2	16.7	3.0	491	B
May 9	10.3	11.5	3.2	110	C
May 10	10.0	10.7	2.6	147	C
May 28	12.6	13.3	2.2	169	C
July 3	15.8	16.6	2.3	224	C
August 14	19.3	21.0	2.3	117	C

Inter-comparisons between monitoring points yielded diverse relationships, with no discernible pattern or consistency over the various days of observation. Local temperatures (i.e. at each point location) are interpreted in terms of relative differences to the reference station located at GCU. Figure 2 shows all differences obtained, superimposed day by day.

Figure 2: Relative air-temperature differences to the reference station located at GCU, day by day

Correlations found between relative differences to the reference weather station at GCU and each point's SVF were varied, ranging -0.56 to 0.37 (with a mean of -0.01), with inverse and direct relationships between urban density and local air temperature depending on daytime weather conditions on a given day.

The interpretation of temperature difference data, when accounting for atmospheric stability is shown in Figure 3. For each PGT class, a mean daytime pattern was determined from the various daytime periods belonging to that particular class.

Figure 3: Relative air-temperature differences to the reference station located at GCU, accounting for atmospheric stability classes (PGT scheme)

The most stable condition (class C) shows less differentiation between point temperatures. The same finding is confirmed in respect of relative air temperature difference (to the reference weather station at GCU) variations among the 32 monitoring points (Figure 4). Variations are much more pronounced for the first two classes (A and A-B), dropping consistently for the following categories. The explanation for that lies in the fact that stronger radiation and weaker wind speed, which define the most unstable PGT classes, in conjunction with the site's morphology, produce more noticeable effects on intra-urban temperature variability. In terms of morphology, the obtained effects mainly include shading effects resulting from surrounding buildings on a given site.

Figure 4: Relative air-temperature difference variations to the reference weather station at GCU for varying atmospheric conditions – determined from the range of air-temperature differences for all 32 point locations

Strength of correlation due to morphology

The ensemble of points with varying SVF attributes, yet with a particular shape is analyzed separately. From Table 1, points 3, 5, 7, 10, 16 and 23 are within street canyons with an almost E-W axis orientation. Points 20, 30, 31 and 32 are located in open-air sites. The SVF variation in the first set of points is within the range 0.04-0.31; for the second subset within 0.55-0.78. Thus, the SVF variation in both subsets is similar, averaging 0.25.

Correlations between SVF variations and intra-urban temperature differences have been drawn for subsets of the data sample under the full ensemble of atmospheric conditions, namely for the six points located in E-W street canyons and for four points which had greater sky openness (SVF>0.5) (Figure 5). As such correlations refer to a limited number of points, absolute values do not possess statistical strength, though overall trends (direct or inverse relationship to SVF) can be regarded as indicative of morphology effects on local air temperature. For the points located in E-W street canyons, correlations between relative air temperature differences to the reference weather station at GCU are mostly positive (20 out of 23 days), irrespective of atmospheric patterns. For the open-air sites, correlations are normally negative (again, 20 out of 23 days) exhibiting an inverse relationship between SVF and air temperature variability. An explanation is that in more constrained locations, solar radiation gains in the canyon will increase heat trapping and enhance sensible heat, whereas open-air locations promote more heat losses due to ventilation; in the first case, radiation is the driver, in the latter, air movement.

Figure 5: Correlations between relative air-temperature difference variations to the reference weather station at GCU and SVF attributes

Patterns of relationship between relative difference variations and atmospheric classes are not as strong as for the whole dataset (i.e., for all 32 points) for the canyon situations and are virtually nonexistent in the case of the open-air locations, which shows that such factor (atmospheric stability) loses its explanatory power entirely in less constrained locations (Figure 6).

Figure 6: Relative air-temperature difference variations to the reference weather station at GCU for varying atmospheric conditions – a) for E-W street canyons, b) for open-air locations

Thermal comfort

The thermal votes obtained in the outdoor comfort campaigns over late winter, spring and summer 2011 were binned for each one-degree centigrade variation in ambient temperature. Figure 7 shows the obtained graph for the range of air temperatures monitored, with respective (binned) thermal sensation votes.

Figure 7: Binned thermal sensation versus air temperature Ta (from outdoor comfort campaigns)

The regression line and formula give us a comfort band between 11 and 16°C (Ta) where the reported mean thermal sensation (MTS) lies within -0.5 and +0.5 thermal sensation vote, normally assumed to be a feasible comfort range [44].

Using the regression formula, the maximum MTS increase relative to the reference weather station at GCU for the 23 traverse days resembles the drop of intra-urban temperature variations shown in Figure 4 with rising atmospheric stability. The first two classes (A and A-B) show a maximum rise in thermal sensation corresponding to a change in MTS category,

e.g. moving from 'neutral' to 'slightly warm' or from 'slightly warm' to 'warm'. In terms of heat stress situations assuming a minimum threshold of 16°C for Glaswegians, 17 out of 23 days were above that threshold at the reference station. The average increase in the transect points resulted in 19 out of 23 days with heat stress.

Dominant atmospheric class in summer for Glasgow

Continuous data for 2011 (solar radiation and wind speed), measured at the reference weather station at GCU, allow us to assess the most frequent atmospheric stability classes during daytime in summer in Glasgow, thereby confirming the trend obtained during the monitoring days. From Table 3, the dominant class is A-B (9 out of 23 days or 40% of the total traverse days). Hourly data for 2011 were interpreted in terms of daytime periods (when solar radiation was present) for a total of 85 days between summer solstice and fall equinox, disregarding gaps in the dataset. From that total, 47% of the days exhibited an A-B atmospheric condition according to the PGT classification scheme.

SUMMARY AND CONCLUSIONS

In summary, results from the traverse study lead us to conclude that accounting for background atmospheric conditions is advisable to better explain intra-urban temperature differences during daytime. Temperature variations will tend to be more accentuated in less stable atmospheric classes, under sunny conditions with light wind, with more remarkable effects on pedestrian thermal sensation. Furthermore, differences in air temperature are noticeable in urban canyons, with a direct correlation to the site's SVF (or sky openness) and with an inverse trend under open-air conditions. Finally, it has been found that the dominant PGT class for summer time in Glasgow is among the classes which yielded the highest intra- urban variability. Such results complement findings related to Glasgow's Urban Heat Island intensity [21]. In that study, it had been found that, from a set of urban and suburban temperature/relative humidity (T/RH) stations, intra-urban air temperature differences during nighttime were accentuated when accounting for Pasquill-Gifford-Turner (PGT) stability classes.

As pointed out by Eliasson and Svensson [29], the effect of different surface coverings on air temperature patterns is more pronounced during clear and calm weather with high air stability. Windy and cloudy conditions smooth out these differences. In this sense, our results confirm such expected behavior (cf. Figure 3).

Considering predicted increases in frequency, intensity and duration of heat-wave episodes [45,46,47] and consequences of outdoor exposure to extreme heat or less so to warmer conditions in summer, pedestrian areas can be seriously affected in terms of a drop in the number of visitors and as regards their attractiveness [48]. Furthermore, cities like Glasgow could be seriously impacted in terms of mortality. As pointed out by Gronlund et al. [49], heat-related mortality was found to be stronger particularly in North-American cities with milder summers and lower air conditioning prevalence. Thus, improvements in outdoor thermal conditions to be met by sound urban design measures should be sought in those areas.

From the trends shown in this paper, further work should focus on urban density transitions (here expressed as the site's SVF, though other morphology indicators could and should additionally be tested in the future) that affect the pattern of relationship between local air temperature and built density, as observed in Figure 5. Parametric analysis could be performed by means of computer simulation in order to draw additional conclusions on the effects of density and local air temperature when accounting for given orientations, seasons of the year and day types. Finally, it should be stressed that the sample obtained shows limitations in terms of the characteristics of the points surveyed.

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Figures

Figure 1: Study area with monitoring points and traverses

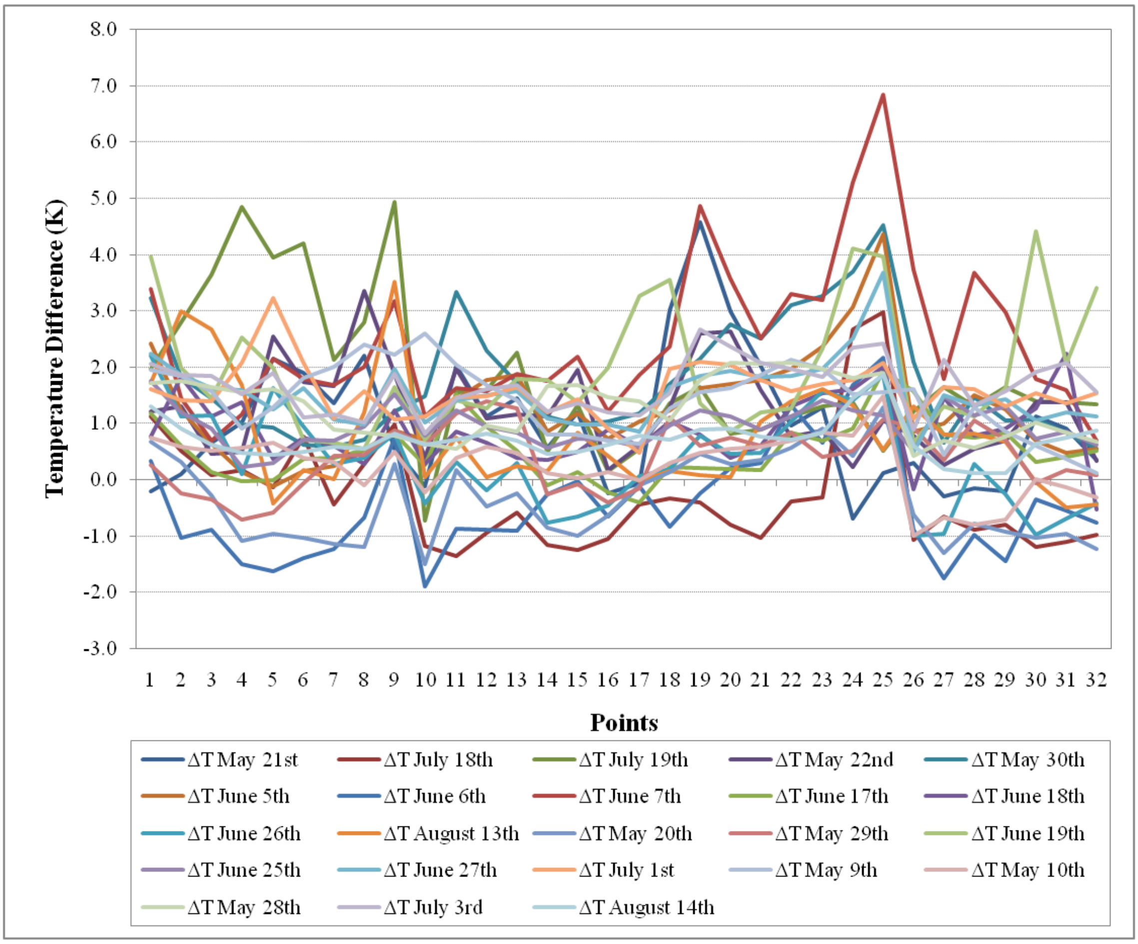


Figure 2: Relative air-temperature differences to the reference station located at GCU, day by day

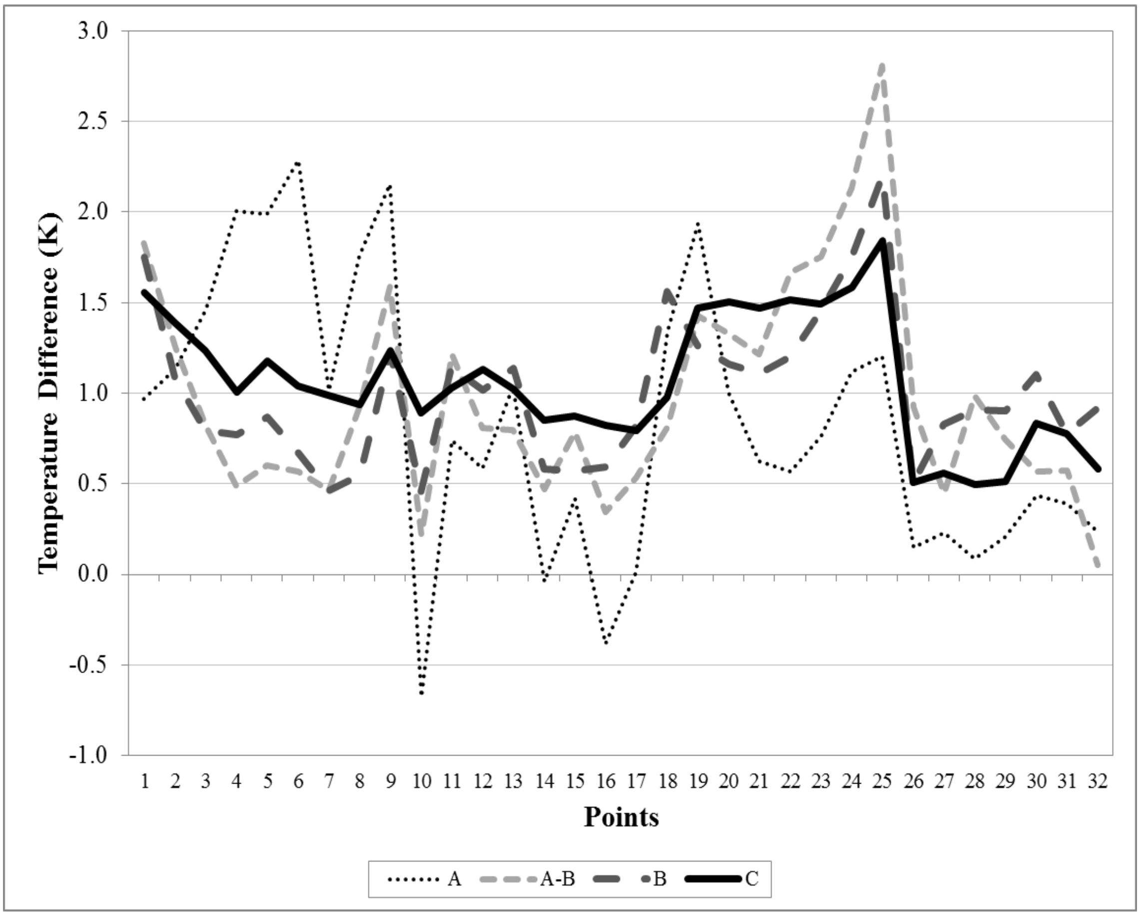


Figure 3: Relative air-temperature differences to the reference station located at GCU, accounting for atmospheric stability classes (PGT scheme)

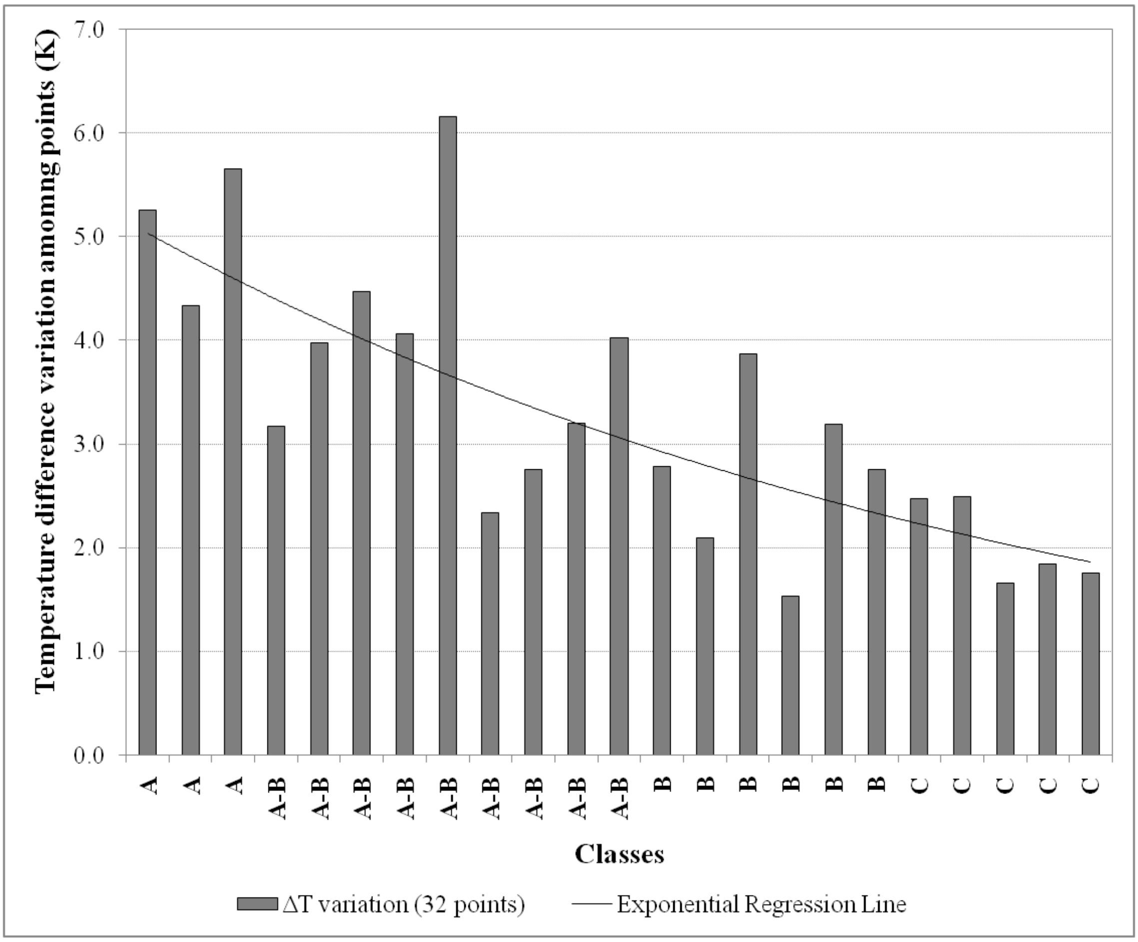


Figure 4: Relative air-temperature difference variations to the reference weather station at GCU for varying atmospheric conditions – determined from the range of air-temperature differences for all 32 point locations

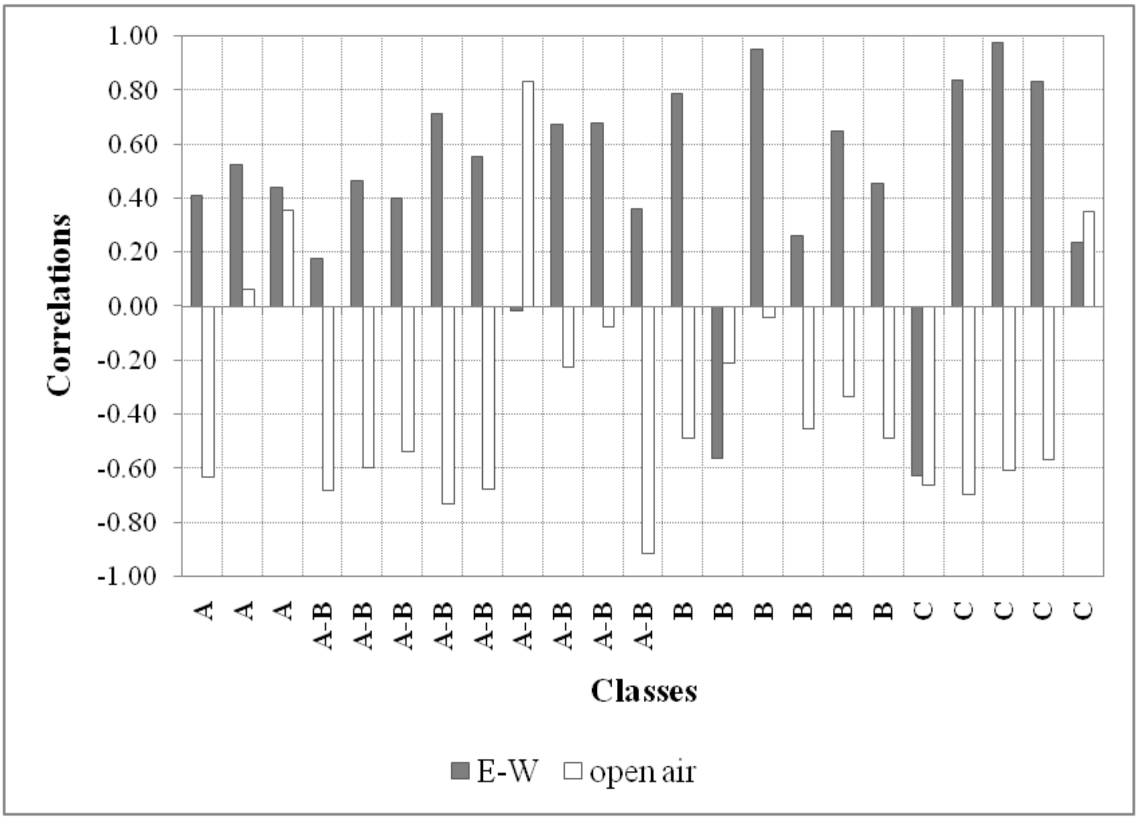
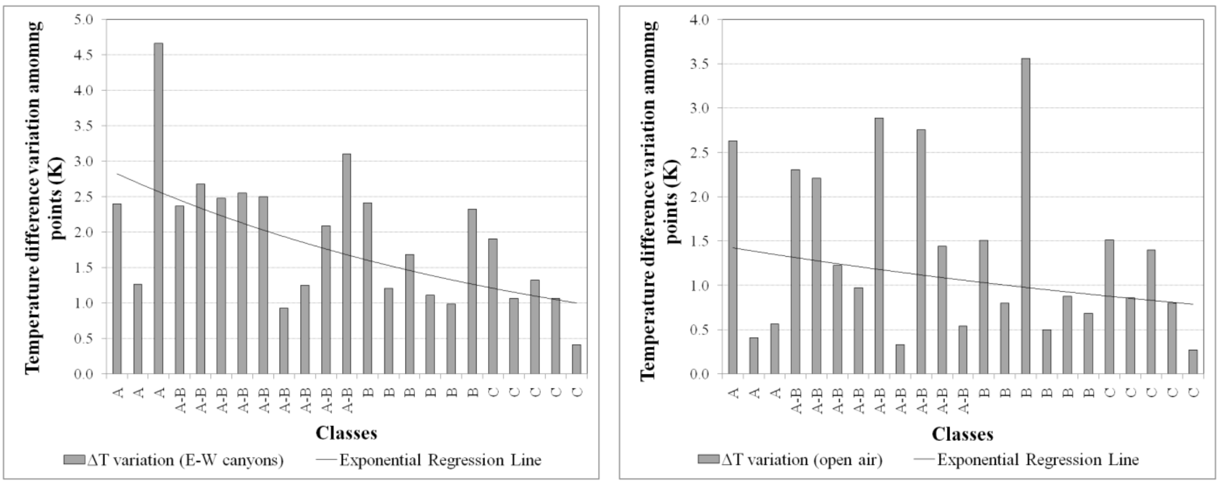


Figure 5: Correlations between relative air-temperature difference variations to the reference weather station at GCU and SVF attributes



a) b)

Figure 6: Relative air-temperature difference variations to the reference weather station at GCU for varying atmospheric conditions – a) for E-W street canyons, b) for open-air locations

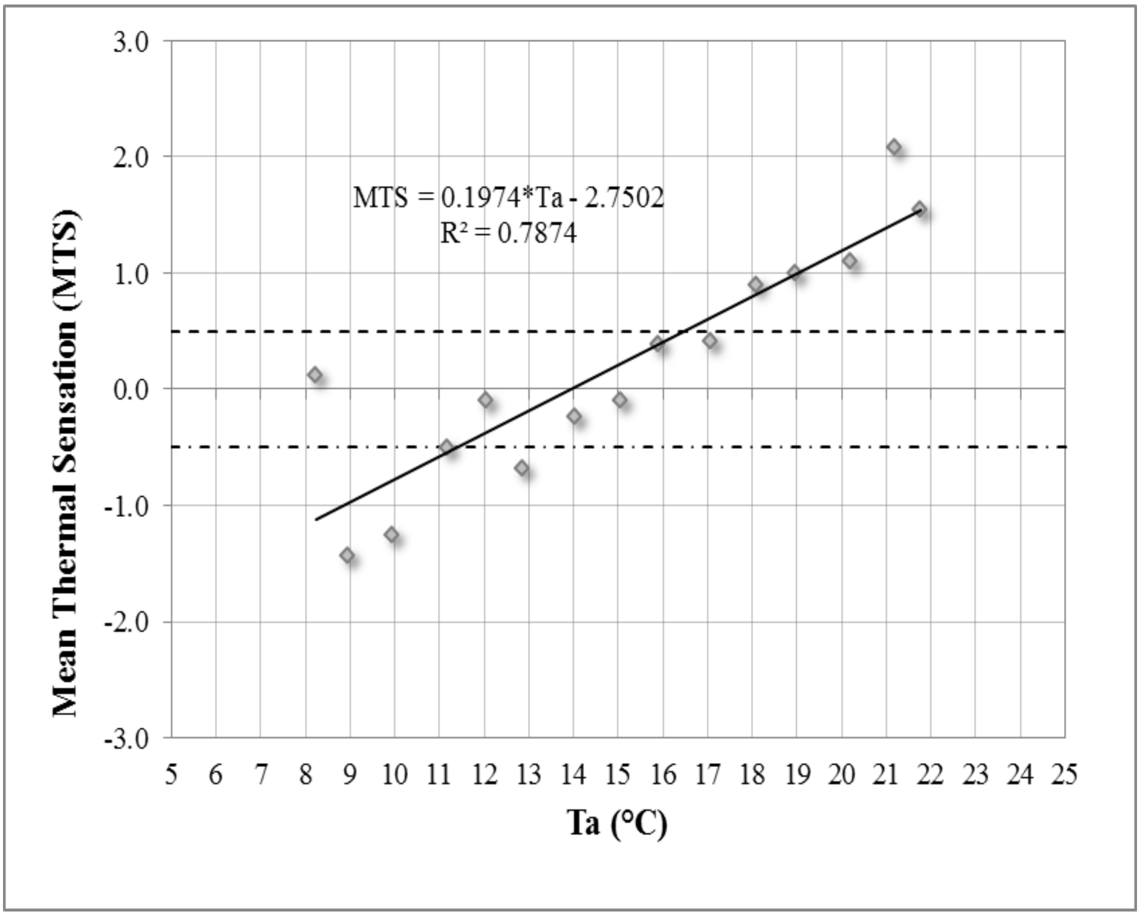


Figure 7: Binned thermal sensation versus air temperature T_a (from outdoor comfort campaigns)